Frequency-Stabilized Diode-Pumped Tm,Ho:YLF Local Oscillator with ±4 GHz of Tuning Range

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ABSTRACT

A tunable, single-frequency, frequency-stabilized, diode-pumped Tm,Ho: YLF laser is described. The laser, which demonstrates the function of a local-oscillator for coherent Doppler lidar in space, has continuous frequency tunability of more than 8 GHz. Active frequency stabilization is achieved by feedback electronics which allow for controlled tuning capability. Output power of more than 20 mW in single-transverse and -longitudinal mode operation with a short term frequency jitter of less than 100 kHz/ms is obtained.

Key-words: Tm,Ho: YLF, 2-Micron Laser, Coherent Lidar, Frequency-Stabilization, Frequency-Agility

1. INTRODUCTION

For several years NASA has recognized the need for an eye-safe solid-state laser technology which has the capability to be used for Earth-orbiting Doppler wind lidar. In order to measure atmospheric wind fields on a global scale with suitable horizontal (~ 100 km) and vertical (0.5 - 1 km) resolution, pulse energies of at least several hundred mJ and an average output power of at least 2 W are needed from a single-frequency, diffraction-limited transmitter in a coherent Doppler lidar. High electrical-to-optical efficiency is very important due to limited power resources available on candidate spacecraft. The Tm,Ho:YLF laser medium has been favored for development support due to its eye-safe 2-μm wavelength and relatively favorable laser properties, including the ability to be optically pumped with diode lasers near 790 nm wavelength. Developments of transmitter technology using a design employing single-frequency (injection-seeded) oscillator followed by multiple amplifiers, with pulse lengths sufficient for Doppler shift measurements of 1-2 m/s with high efficiency, have been recently reported [1,2].

A frequency-agile local oscillator is essential for an Earth-orbiting Doppler lidar which scans at one or more off-nadir angles and several azimuth angles in order to provide wind fields in a swath near the sub-orbital track of the spacecraft. At the lidar wavelength, the motion of the spacecraft induces Doppler shifts of as much as 6-10 GHz in the frequency of the transmitted and backscattered radiation as the azimuth varies from forward to aft looks, for nadir angles which are suitable for the measurements of the horizontal wind component. However, photomixers with the required high quantum efficiency are not available with bandwidths of 8 GHz or more at the lidar wavelength. Since a scanning lidar (e.g., conical scan) will experience a spacecraft-induced Doppler shift which is variable and synchronous with the azimuth angle of the scan, it is necessary that the local oscillator be tuned synchronously with the azimuth angle of the scan in order to track out and compensate for this component of the Doppler shift of the backscattered radiation. Furthermore the short-term (few ms time period) frequency jitter should be significantly less than 1 MHz in order for wind measurements to be made with velocity resolution of ± 1 m/s.

Steady progress has been made in frequency-agile local oscillator design and tunability over the past few years, with demonstration of high CW efficiency [3] followed by demonstrated continuous tunability [4,5] reaching the point where we now report continuous tunability over more than 8 GHz.

2. LASER SETUP

A fiber-coupled laser diode (SDL-2372-P3) capable of outputting as much as 1.3 W of power at 794 nm is used to end-pump a small Tm, Ho: YLF laser crystal. In earlier experiments, the Tm, Ho : YLF laser crystal has demonstrated the highest-gain amplification [6]. The crystal dimensions are 5x5x2 mm^3 where the 2-mm length is along the optical axis. The composition of the laser crystal was described in an earlier publication [7]. A relatively short laser cavity (about 15 mm) facilitates broad tuning and minimizes undesired modes. To achieve high output power in a single longitudinal mode, the pump diode array was driven at 2 A producing about 1 W of pump power focused on the Tm,Ho:YLF crystal. The pumped surface of the crystal is high reflectance coated at 2060 nm while having a high transmittance at 794 nm. The opposite surface is anti-reflectance coated at 2060 nm. An output-coupler mirror with radius of curvature of 50 mm and reflectanceof 98.5% at 2060 nm was bonded to a cylindrical-shape piezo-electric transducer (PZT). Due to the close coupling of the lower laser level and the ground state of the Ho ion, optical-to-optical conversion efficiency is improved with lowering the crystal temperature. The crystal is tightly fitted into a copper housing. A dual stage thermoelectric cooler (TEC) is used to cool the crystal to -10 °C. Heat from the thermo-electric coolers is dissipated through the laser base and onto its adjoining platform. The optical mounts are tied together with steel rods and mounted on an aluminum baseplate. The laser assembly is in an enclosed environment and is gently purged with dry nitrogen to prevent moisture condensation on the crystal. Use of water cooling was avoided to prevent mechanically-induced jitter in the beat-note. The laser is passively isolated from environment (mostly acoustic) vibrations by utilizing foam rubber pads. An schematic of the setup is shown in Figure [1].

To enforce a single longitudinal mode of operation along with both high power output and a broad frequency tuning range, two etalons are placed inside the laser cavity. These are uncoated fused silica plates with parallel surfaces and thicknesses of 0.1 mm and 0.2 mm. The laser's output is monitored for broad-tunability while maintaining single mode operation when the etalons are angle-tuned. A single etalon can also induce single longitudinal mode operation but at lower small signal gain ad over a more much limited tuning range. Application of higher pump power and subsequent frequency tuning was found to induce mode hopping and multi-moding.

To characterize the performance of the lasers via the heterodyne technique, two such single-frequency lasers with identical cavity structure were constructed. From here on, in this paper, we will refer to the two lasers as the local oscillator (LO) and the injection laser (IL). The beams from the two lasers were mixed on a 1.7 GHz bandwidth InGaAs (Sensors Unlimited) photodiode. An electronic stabilization loop depicted in Figure [2] was used to frequency tune the intermediate frequency (IF_1) beat-note.

A separate bias current of 1 mA is applied to the photomixer to increase its sensitivity. The RF signal from this photomixer (IF_1) is amplified by 75 dB and sent into an RF mixer t be combined with the output of a 1-2 GHz voltage controlled oscillator (VCO). The RF mixer outputs the difference(IF_2) between the VCO frequency and the photomixer beat-note. This difference frequency feeds into a 1 GHz RF discriminator. When IF_2 deviates from 1 GHz, either a positive or a negative error signal is generated which feeds into an analog integrator unit. The integrator output drives a high voltage amplifier whose output is applied to the LO laser PZT. In the fixed locked-feedback-mode,the LO laser frequency remains at a steady frequency with respect to the IL. The LO laser has three distinct modes of operation:

1. <u>Open Loop Operation</u>
   Allows for broad ± 4 GHz manual tuning, but, does not correct for LO drift, or greater than 1 MHz of jitter.

2. <u>Locked Fixed Frequency</u>
   A fixed frequency (0 to 1 GHz) is chosen and the feedback-loop is engaged to lock the LO at this frequency. Drift is eliminated and jitter is reduced.

3. <u>Scanning Locked Mode</u>
   A low frequency (< 1 Hz) sine wave is applied to the loop VCO control voltage. This in turn causes the IF_1 beat-note to scan ± 1 GHz in a controlled, locked and regulated manner eliminating long term drift and reducing jitter.

To facilitate RF beat-note acquisition between the LO and the IL, we constructed an air-spaced Fabry Perot (FP) etalon with a free spectral range (FSR) of > 1000 GHz. Without the wide FSR etalon, close overlap of the modes from the two lasers (within the bandpass region of our photomixer) was found to be very difficult. A separate 3 GHz commercial FP is used to evaluate the broad tuning range of the LO. Since the photomixer has an RF cutoff frequency of 1.7 GHz use of the 3 GHz FP is essential to insure that the LO actually tunes ± 4 GHz with respect to the IL source.

3. EXPERIMENTAL RESULTS

The local oscillator laser characteristics are summarized below:

LaserParameters	**Requirements**
Wavelength (nm)	2060±10
Longitudinal Mode Quality	Single
Output Power (mW)	≥ 28
Power Stability	< 5% p.p., 1 sec
Output Polarization	98%, Linear
Long-Term Frequency Jitter (KHz)	± 0.8 MHz
Continuous Frequency Tuning Bandwidth (GHz)	≥ 7.9
Average Tuning Speed (GHz/sec)	1.3
Maximum Tuning Speed (GHz/sec)	± 4.1
Loop Settling Time (ms)	65

The overall laser efficiency is reduced because of the need to maintain both single longitudinal mode output and the required broad tuning range. Prior to introducing the etalons to the cavity, the laser operates with several longitudinal modes. Laser output powers as high as 80 mW are measured. The system remains locked for as long as six hours at a time, to be disturbed mainly by acoustic frequencies in the range of < 1 KHz. To observe the system jitter, a fixed beat-note frequency is chosen and the laser is feedback-locked at this point. Direct viewing of the photomixer beat-note on an RF spectrum analyzer is accomplished by having an RF splitter in the loop amplifier chain. The spectrum analyzer is set to a slow sweep speed and a narrow span. The measured jitter of approximately 0.8 MHz is primarily due to ambient acoustic noise coupling into the laser cavity structures (both the LO and IL). The measured beat-note frequency jitter could be further reduced by acoustically isolating the lasers from background noise.

The LO stabilization loop must be able to increment the beat-note quickly enough to track out the orbital Doppler shift associated with the system scanner positioning. Total scanner increment and settling time is >100 ms. Tests of the LO show that it has a loop settling time of < 70 ms.

The photomixer used in loop stabilization would ideally have a bandwidth of 4 GHz in order to allow active loop feedback stabilization to 4 GHz. Since the photomixer is bandwidth limited to 1.7 GHz, active stabilization becomes difficult beyond this frequency. Further experiments will be conducted in an attempt to lock onto diminished RF levels so that an active loop can be maintained across the desired tuning range. We recently acquired a very broadband ultra-low noise RF amplifier which has enabled us to view the beat-note out to 5 GHz although its -3 dB point is still at 1.7 GHz.

Long term mode drift occurs in both the LO and IL causing the IL frequency to no longer be precisely centered with respect to the LO. In the laboratory this drift requires a periodic adjustment of the IL's PZT voltage so that its frequency is again centered with respect to the LO. Development of an automated system that maintains a symmetrical tuning range while avoiding tuning regions which induce mode hopping is planned.

Figure [3] shows a picture of the local oscillator source described above. To optimally utilize this local oscillator laser in space, more compact packaging, drift of the single-frequency mode, use of partially-coated etalons and the bandwidth limitations of the photomixer diode deserve further attention.

4. ACKNOWLEDGMENTS

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the national Aeronautics and Space Administration (NASA). The authors are thankful to James Lesh and David Haner for helpful discussions.

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Figure (1). Schematic of the Frequency-Agile Local Oscillator

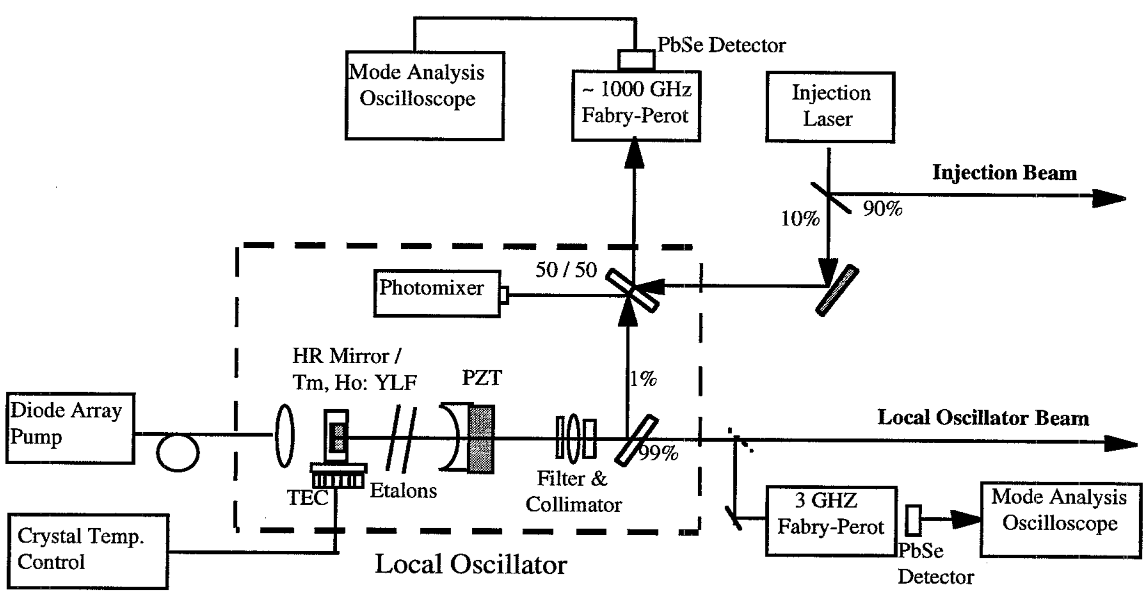

Figure (2). Frequency Agile Local Oscillator
Frequency Stabilization & Tuning Electronics

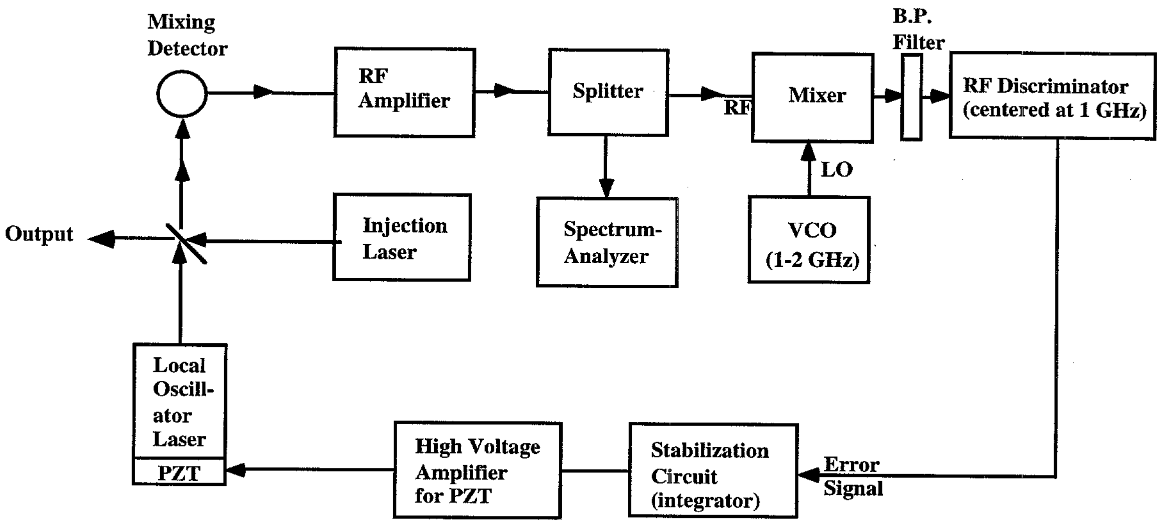

Figure (3). Picture of the Local Oscillator